

CHARGE SYMMETRY VIOLATION IN NUCLEAR PHYSICS

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ABSTRACT

The study of charge symmetry violation in nuclear physics is a potentially enormous subject. Through a few topical examples we aim to show that it is not a subject of peripheral interest but rather goes to the heart of our understanding of hadronic systems.

1. Introduction

The concept of charge symmetry (CS) is not as familiar as that of charge independence. Whereas the latter requires that the Hamiltonian, H , commutes with all the generators of rotations in isospace ($[H, I_i] = 0, \forall i = 1, 2, 3$), the former requires only that H be invariant under rotations by 180° about the 2-axis in isospace:

$$[H, e^{i\pi I_2}] = 0. \quad (1)$$

Thus while isospin is frequently broken at the level of a few percent, CS is often good to a fraction of a percent¹. For example, the mass splitting between the proton (p) and the neutron (n) is only a 0.1% effect.

The classic place to test CS is in nucleon-nucleon (NN) scattering. This is an area where there have recently been some very important new experiments and some fairly significant new theoretical ideas. Section 2 is devoted to these issues. In section 3 we review recent developments in the treatment of charge symmetry violation (CSV) in mirror nuclei – the Okamoto-Nolen-Schiffer anomaly. We specifically discuss recent quark-based treatments of this effect. In this meeting quite a lot of attention was devoted to the use of nuclear data to extract the element V_{ud} of the Cabibbo-Kobayashi-Maskawa matrix, in order to test whether the matrix is unitary. In section 4 we outline some recent work which suggests the apparent violation of unitarity may

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be (at least) partially explained in terms of the CSV change in the structure of bound p 's and n 's.

2. The Class IV NN Force

In the terminology of Henley and Miller² a class IV force affects only the np system, mixing spin-singlet and triplet states. Experimentally it is extremely difficult to detect such a mixing which gives rise to a difference between the asymmetry measured in $\vec{n}p$ and $\vec{p}n$ scattering (i.e. $\Delta A = A_n(\theta) - A_p(\theta) \neq 0$) at the 10^{-3} level. The experimental determination of this CSV at TRIUMF³ and IUCF⁴ has been a superb achievement and some of this is captured in the presentation of van Oers at this meeting⁵.

The theoretical contributions to the class IV interaction have been well understood for some time^{6,7,8} – at least within the framework of one-boson-exchange forces. There is a characteristic difference in the energy dependence of the contribution of the CSV force arising from the np mass difference at the nucleon vertex when a charged, isovector meson is omitted (proportional to $(\vec{\tau}_1 \times \vec{\tau}_2)_z (\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \vec{L}$) and that arising from γ -exchange or ρ - ω mixing (proportional to $(\vec{\tau}_1 - \vec{\tau}_2)_z (\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{L}$). At energies above $300 MeV$, where the TRIUMF experiments have been performed, there is essentially no sensitivity to the latter contribution, while at the energy of the IUCF experiment ΔA is 20 without, and 35 with, ρ - ω mixing – in comparison with the experimental value of $33 \pm 5.9 \pm 4.3$ (all in units of 10^{-4}).

Clearly the experiments are complementary, with the second generation TRIUMF experiment confirming the prediction of Holinde *et al.*⁷ – see also Ref.⁹ – quite precisely and thus confirming our understanding of the pion exchange component of the NN force. The effect of ρ - ω mixing is then confirmed by the IUCF measurement, but only at the level of $1 - 2\sigma$. In view of the theoretical interest surrounding ρ - ω mixing, which we describe next, and especially its vital role in the conventional treatment of CSV in mirror nuclei^{1,10}, it is extremely important to make a second generation experiment at an energy below $200 MeV$!

2.1. Meson Mixing and Vector Meson Dominance

The mixing between a “real” ρ and ω is, of course, observed in the measurement of the pion form-factor in $e^+ - e^-$ annihilation. However, in calculating the usual CSV NN potential it is assumed that there is no variation of the mixing amplitude from m_ρ^2 to the space-like region (where it is needed to construct the potential) and that there is no CSV at the $NN\rho$ or $NN\omega$ vertices^{2,11}. Goldman *et al.* (GHT)¹² were the first to ask whether it was reasonable to assume that the ρ - ω mixing amplitude is independent of q^2 and there has since been a considerable body of work.

The initial GHT model was relatively simple. The vector mesons were assumed to be quark-antiquark composites, and the mixing was generated entirely by the small

mass difference between the up and down quark masses. The mesons coupled to the quark loop via a form-factor which modelled the meson substructure. Free Dirac propagators were used for the quarks, thus ignoring the question of confinement. More recent work^{13,14} has modelled confinement by using quark propagators which are entire (i.e. which do not have a pole in the finite complex- q^2 plane so that the quarks are never on mass-shell). The vector mesons couple to conserved currents which, as shown by O’Connell *et al.*¹⁵, leads to a node in the mixing amplitude when the momentum (q^2) of the meson vanishes.

The use of an intermediate nucleon loop¹⁶ as the mechanism driving $\rho - \omega$ mixing amplitude (relying on the mass difference between the neutron and proton) avoids the worries of quark confinement, as well as enabling one to use well-known parameters in the calculation (masses, couplings, etc). This model has a node for the mixing at $q^2 = 0$. Mitchell *et al.*¹⁴ concluded that in their bi-local theory (where the meson fields are composites of quark operators, e.g. $\omega_\mu(x, y) \sim \bar{q}(y)i\gamma_\mu q(x)$) the quark loop mechanism alone generates an insignificant CSV potential.

Iqbal and Niskanen¹⁷ studied the effect of a $\rho - \omega$ mixing amplitude that vanished at $q^2 = 0$ on the CSV np potential and concluded (as GHT had suggested) that it reduced the effect to a negligible level. The idea that the mixing amplitude should vanish at $q^2 = 0$ was challenged on the grounds that for the same reasons the $\gamma^*\rho$ coupling should vanish there and this would destroy the phenomenological success of vector meson dominance (VMD)¹⁸. In a recent review of VMD, O’Connell *et al.*¹⁹ show that while this would be true in the traditional form of VMD, in the original form introduced by Sakurai²⁰ (VMD1 in the notation of O’Connell *et al.*) it is fact quite natural for the coupling to vanish at $q^2 = 0$. In order to guarantee the equivalence of the two formulations one must add a direct photon-hadron coupling in the VMD1 form. That VMD1 can also produce an excellent description of the pion form-factor has recently been shown explicitly²¹. Indeed, it is only in the older version of VMD that one can naturally include any deviation from universality – as observed in nature²².

Returning to the $\rho - \omega$ mixing potential we note that a completely consistent calculation must deal with not only the mixing amplitude but also with the vertices^{23,24} – the independent parts of the full calculation are dependent on the choice of interpolating fields for the vector mesons. Gardner *et al.*²⁵ have recently shown that for a very natural choice of interpolating field (the quark vector current) there is a sizeable CSV at the vertices. This may restore some of the CSV required. Their result is particularly important because for their choice of vector meson fields the result of O’Connell *et al.*¹⁵ shows that the mixing amplitude would indeed vanish at $q^2 = 0$. In conclusion, we note that the one further uncertainty over the CSV potential arising from $\rho - \omega$ mixing is the range of the form-factor used at the $NN\rho$ or $NN\omega$ vertex. If this is as soft as suggested by the work of Deister *et al.*²⁶, for example, the $\rho - \omega$ mixing potential would still be negligible. All of this simply increases the desperate

need for a new measurement below 200MeV .

3. The Okamoto-Nolen-Schiffer Anomaly

The Okamoto-Nolen-Schiffer (ONS) anomaly^{27,28} is a long-standing problem in nuclear physics. The anomaly is the discrepancy between experiment and theory for the binding energy differences of mirror nuclei – after the removal of electromagnetic corrections. Conventional nuclear contributions to the anomaly are thought to be at the few per cent level and cannot explain the experimental findings^{28,29}. The effects of charge symmetry breaking in the nuclear force^{27,30}, especially ρ - ω mixing, seem to reproduce much of the discrepancy^{1,10,31}, at least in light nuclei. However, the investigations of the off-shell variation of the ρ - ω mixing amplitude, discussed in the previous section, have put this explanation into question. As a consequence there has been considerable interest in the development of alternative, quark-based, approaches to the problem.

One of the earliest quark-based treatments of the ONS anomaly was by Henley and Krein³³. Using the Nambu–Jona-Lasinio (NJL) model, they indicated that the anomaly might be related to the partial restoration of chiral symmetry in nuclear matter. More recent theoretical investigations have involved QCD sum-rules³² and the quark cluster model³⁴. In the latter case, Nakamura *et al.* used a quark cluster model of the NN force to incorporate the CSV effect of a quark mass difference in the one-gluon-exchange hyperfine force in a study of nuclei in the $1s - 0d$ shell. This is an ambitious program but the initial results look promising.

We would like to briefly report on the application of the quark-meson coupling (QMC) model of Guichon³⁵ to this problem. In this model, nuclear matter consists of non-overlapping nucleon bags bound by the self-consistent exchange of σ and ω mesons in the mean-field approximation. It has been extended to include the ρ and an isovector-scalar meson (the δ)^{36,37}. As well as providing an excellent description of the properties of nuclear matter, it has been applied successfully to the calculation of nuclear structure functions³⁸. Furthermore, the relationship between the QMC model and Quantum Hadrodynamics (QHD)³⁹ has been investigated. The fascinating result is that for infinite nuclear matter the two approaches can be written in an identical form, except for the appearance of the quark-scalar density in the self-consistency condition for the scalar field³⁶. The simplicity of this finding suggests that it may be rather more general than the specific model within which it was derived.

Retaining only the σ mean field (which gives the dominant effect) the main result of the model for the ONS anomaly is³⁷:

$$\Delta_{np}^* = \Delta_{np}^0 - g_\sigma(C_n^\sigma - C_p^\sigma)\bar{\sigma}. \quad (2)$$

Here Δ_{np}^* is the $n - p$ mass difference in matter of density ρ_B , Δ_{np}^0 is the free mass difference and we have assumed symmetric nuclear matter. The dominant physics

Table 1: Estimate of the ONS anomaly (in MeV) for several finite nuclei using local density approximation – from Ref.³⁷. (R_0 is the bag radius for the free nucleon.)

$R_0(fm)$	0.6	0.8	1.0	observed discrepancy
$^{15}\text{O}-^{15}\text{N}$	0.29	0.32	0.34	0.16 ± 0.04
$^{17}\text{F}-^{17}\text{O}$	0.22	0.25	0.27	0.31 ± 0.06
$^{39}\text{Ca}-^{39}\text{K}$	0.36	0.41	0.44	0.22 ± 0.08
$^{41}\text{Sc}-^{41}\text{Ca}$	0.34	0.38	0.41	0.59 ± 0.10
^{120}Sn	0.72	0.83	0.87	
^{208}Pb	0.78	0.91	0.95	~ 0.9

arises from the nucleon internal structure which means that the σ couples to the nucleon through its scalar density C_j^σ ($j = n, p$), which is density dependent and larger for $j = n$ than for $j = p$ because of the greater mass of the d -quark. Because $C_n^\sigma > C_p^\sigma$ the n - p mass difference decreases as ρ_B goes up.

It is not possible to make an accurate calculation of the CSV effects for finite nuclei using a model of infinite nuclear matter. Nevertheless we can get a qualitative idea using local-density approximation. As seen in Table1 both the sign and the order of magnitude of the anomaly are well reproduced.

In conclusion, we note that although equ.2 was derived within the QMC model it may be a more general result. We see that the internal structure of the nucleon is crucial to the understanding of the ONS anomaly in any relativistic model of nuclear structure involving a scalar field. In particular, if the quarks are relativistic and the n - p mass difference arises because $m_u \neq m_d$, then in matter this mass difference will vary by an amount proportional to $m_d - m_u$ and $\bar{\sigma}$. This variation necessarily has the correct sign and magnitude to explain the ONS anomaly. By comparison the magnitude of the CSV induced by the $n - p$ mass difference in QHD is an order of magnitude too small⁴⁰.

4. Unitarity of the Cabibbo-Kobayashi-Maskawa Mass Matrix

As we have heard at this meeting⁴¹ it is very important to refine our understanding of the weak coupling to quarks. A violation of unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix would be a clear indication of physics beyond the standard model. The precision required for such a test, particularly for the dominant matrix element, V_{ud} , presents a tremendous challenge to experimenters and theorists alike. In particular, the most accurate experimental measurement of the vector coupling constant in nuclear beta-decay comes from super-allowed 0^+-0^+ transitions between nuclear isotriplet states. In order to relate these precise measurements to the quark-level vector coupling, V_{ud} , one needs to apply a number of small nuclear structure

corrections⁴² in addition to the relatively standard radiative corrections⁴³. Despite intensive study of these nuclear “mismatch” corrections^{44,45} there remains a systematic difference of a few tenths of a percent between the value of V_{ud} inferred from the vector coupling measured in muon decay, G_μ , and unitarity of the CKM matrix and those determined from the nuclear ft -values. For recent summaries we refer to the reviews of Wilkinson⁴⁶ and Towner and Hardy⁴⁷, and also to the recent report by Savard *et al.*⁴⁸ of accurate data on ^{10}C .

Until now the nuclear corrections have been explored within the framework of conventional nuclear theory with point-like nucleons. Of course, for the nucleon itself there has been considerable investigation of the effect on the vector form-factor of the breaking of CVC caused by the small u - d mass difference in QCD^{49,50}. While this is necessarily very small, the measurements of V_{ud} and G_μ are also extremely precise. Thus we have been led to ask whether this small nuclear discrepancy might be associated with a change in the degree of non-conservation of the vector current caused by nuclear binding⁵¹.

In order to investigate whether nuclear binding might influence the Fermi decay constant of the nucleon itself one needs a model of nuclear structure involving explicit quark degrees of freedom which nevertheless provides an acceptable description of nuclear binding and saturation. The QMC model, described in the previous section, seems ideally suited to the problem. It allows us to examine the variation with density of the quark vector current matrix element:

$$I_{ii'}(\rho_B) = \int_{Bag} dV \psi_{i/p}^\dagger \psi_{i'/n}, \quad (3)$$

with $i' = d$ and $i = u$ for the $d \rightarrow u$ conversion and $i = i' = u$ or d for the two spectator quarks. As the radius of the proton and neutron are different we integrate over the common volume.

The decrease in $I_{ii'}$ as the density increases is a direct consequence of the increasing difference between the proton and neutron radii – that is the smaller volume of overlap. In the calculation of Saito and Thomas⁵¹ the deviation of $I_{ii'}(\rho_B)/I_{ii'}(0)$ from unity is roughly linear with density:

$$\frac{I_{ii'}(\rho_B)}{I_{ii'}(0)} \simeq 1 - a_{ii'} \times \left(\frac{\rho_B}{\rho_0} \right), \quad (4)$$

with $a_{ii'} \simeq (2.4, 2.9, 3.3) \times 10^{-4}$ for $R_0 = (0.6, 0.8, 1.0)$ fm, respectively, (for any combination of ii') and ρ_0 the normal nuclear density (0.17 fm^{-3}).

The evaluation of ft -values involves the inverse of the product of I_{ud} , I_{uu} and I_{dd} squared. Since for a given, free (average) radius of the bag each of these matrix elements decreases by roughly the same amount, the fractional increase in the ft -value with density is therefore

$$\frac{ft(\rho_B)}{ft(0)} \simeq 1 + b \times \left(\frac{\rho_B}{\rho_0} \right), \quad (5)$$

with b approximately six times the decrease in each integral – i.e. $b \simeq (1.5, 1.8, 2.0) \times 10^{-3}$ for $R_0 = (0.6, 0.8, 1.0)$ fm. Thus the *increase* in the ft -value at $\rho_0/2$ ranges from 0.075% to 0.10%, while at ρ_0 it lies between 0.15% and 0.20%. This is to be compared with a violation of unitarity of the CKM matrix of $0.35 \pm 0.15\%$ in the most recent analysis of Towner and Hardy⁴⁷.

While it is not possible to draw unambiguous conclusions from a comparison of theoretical results in infinite nuclear matter with data from finite nuclei, these results are extremely encouraging. At $\rho_0/2$ the calculation suggests a reduction in the violation of unitarity by about $1/3$, while at ρ_0 a correction as big as 0.2% brings the discrepancy back to only one standard deviation.

The essential physics involved in this calculation is CSV, in particular, the fact that *in nuclear matter* the confining potential felt by a quark in a proton is not the same as that felt by a quark in a neutron. We have already explained that a relativistic field theory only yields the right order of magnitude for nuclear charge symmetry breaking if the relevant mass scale involves quarks rather than nucleons⁴⁰. In this sense the ONS anomaly may prove to be something of a “smoking gun” for quark degrees of freedom in nuclei. This is even more obvious here; it is only because the nuclear charge symmetry violation occurs at the quark level that it can produce a deviation of the vector form factor of the bound nucleon from its free value.

5. Conclusion

In this brief review we have seen that charge symmetry violation provides a very specific and powerful tool to probe the nuclear force. Through studies in the NN system we have been led to a deeper understanding of $\rho - \omega$ mixing and indeed of vector dominance itself. In struggling to understand the ONS anomaly in mirror nuclei we have confronted the role of quark degrees of freedom in nuclei. As we have seen, a treatment of nuclear structure at the quark level may also be required to understand the apparent violation of unitarity for the Cabibbo-Kobayashi-Maskawa matrix when V_{ud} is extracted from super-allowed Fermi beta-decay. There can be no doubt that further study of charge symmetry violation in hadronic systems will continue to provide a wealth of information on strong interaction dynamics.

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7. References

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